VIII. Spacecraft Power

GUIDANCE AND CONTROL DIVISION

A. Review of Radioisotope Thermoelectric Generators for Outer Planet Missions,

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1. Introduction

A decision to use a particular type of radioisotope thermoelectric generator (RTG) for the outer-planet missions must be based on a comprehensive review of the capabilities of all the RTG programs which could be applicable. For the most part, the RTG technology that is available is based on lead telluride (PbTe) thermoelectric material, and the status of readiness varies from preliminary design to flight qualified. The nominal performance is given for each RTG system, and an estimate is made of long-term performance of the more suitable RTG systems. The RTG characteristics which are of greatest interest are specific power (W/kg), and the degree of confidence in acceptable performance for the long mission times associated with outer-planet missions. There are many other factors of interest in evaluating an RTG, but these two are the most critical.

The RTG programs which are reviewed are: SNAP 19 *Nimbus*, SNAP 27 *Apollo*, *Transit* (Isotec), *Pioneer* (SNAP 19-TAGS), SNAP 27 Integral, and the Multi-Hundred Watt (MHW). The performance is derived from flight data or current manufacturer's design estimates. The long-term performance projections are based on the most useful module data with extrapolation to longer time periods.

2. Discussion and Results

The results of a review of current RTG programs is shown in Table 1 where the values for several design parameters are shown for all RTG systems of interest. The generator data is divided into two areas, the converter and heat source. All the systems except the MHW are based on PbTe thermoelectric materials. Of the PbTe systems, only the Isotec design is not sealed to limit PbTe sublimation. The Isotec design reduces the temperature level so that the rate of material sublimation is acceptable. The remaining systems are sealed and have a cover gas to suppress thermoelectric material sublimation.

The two current flight programs, SNAP 19 *Nimbus* and SNAP 27, cannot be directly applied to an outer-planet mission. The SNAP 19 performance is too low (< 2.2 W/kg), and SNAP 27 does not have an integral heat source required for an unmanned system. The *Pioneer* program is heavily based on the *Nimbus* generator, with the significant converter modification being the substitution of the TAGS material for the 2P material for better performance and life characteristics. In

Table 1. RTG performance characteristics

Parameters	*Nimbus* SNAP 19	*Apollo* SNAP 27	*Transit* (Isotec)	*Pioneer* (SNAP 19-TAGS)	SNAP 27 Integral	MHW[e]
Converter						
Specific power, W/kg						
BOL	2.15	3.57	2.93	3.11	2.82	4.68
EOL	1.81	3.54	2.37	2.55	2.46	3.72
Power, W						
BOL	28.1	71.0	37	40.9[a]	62.4	155
EOL	23.5	68.8	30	33.5[b]	54.5	123
Weight, kg	8.5	12.4	5.6	8.3	11.5	15.2
RTG	13.0	19.3	12.6	13.1	22.1	33.0
Mission time, yr	1	1	5	2.5	5	12
Efficiency						
BOL	4.5	4.8	4.62	6.4	4.46	7.05
EOL	3.76	4.65	3.75	5.23	3.83	5.6
Hot-junction temperature, °K	794	850 (day) 816 (night)	673	805	833[c] 811[d]	1373
Size diam × length, cm	48.3 × 53.3	39.9 × 45.7	58.4 × 43.2	39.9 × 28.4	30.7 × 46.7	35.3 × 50.8
Heat source						
Heat load, W(t)	625	1480	800	640	1400	2200
Weight, kg	4.51	6.92	6.18	4.93	10.58	17.86
Specific power, W(t)/kg	139	215	129	130	132	123
Operational temperature ,°K						
Surface	866	1022	778	866	NA	1450
Structure	1108	1022	1005	1300	NA	NA
Status	Flown	Flown	Prototype	Prototype	Study	Preliminary design

[a]At fueling.
[b]3.25 yr after fueling.
[c]For 1-yr mission.
[d]For 5-yr mission.
[e]SiGe thermoelectric material.
NA = not applicable.
BOL = beginning of life.
EOL = end of life.
MHW = Multi-hundred Watt

addition, the heat source is based on the Atomics International (AI) advanced capsule technology. Data is also shown for an integral SNAP 27, i.e., one with an integral heat source. The current reference design for the MHW program is also listed and is the only generator using silicon germanium (SiGe) thermoelectric materials. The evaporation rate for the SiGe materials is considerably less than for PbTe, and it may not be necessary to seal the generator to suppress evaporation even at high temperatures (1373°K) and long missions (10 yr). Other factors, such as prevention of oxidation of multi-foil insulation on the pad, may require the RTG to be sealed initially.

The RTG technologies of interest for further consideration are Isotec, SNAP 19-TAGS, and SNAP 27 Integral as well as the MHW. The long-life performance of each of these systems has been evaluated for possible use in outer-planet missions; the results of these evaluations are discussed in *Subsection 3.*

3. Isotec Technology

The Gulf General Atomic (GGA) Company is developing the Isotec technology for use in the *Transit* program. There has been a significant amount of testing in the Isotec program, including two-couple tests (1900 hr), *p*-element tests (24000 hr), and *n*-element tests (16,000 h). There have been two tests of panels which incorporate current design techniques; these are the PG05, which is a single panel tested for 10,000 h, and GC04, a ten-panel module tested for 5300 h. A prediction of long-life performance is based on these two tests extrapolated to 5 yr. Since the tests are conducted at constant heat input, a correction is made for the effects of isotope decay.

The test data shows an average 6-mo degradation at the rate of 10% per year. The longer test (PG05) shows a reduced rate of degradation of 4% per year during the second 6 mo of testing. Assuming the material effects continue at this rate, the total degradation at 5 yr would be about 23%. The full effects of 5 yr of isotope decay ($Q/Q_0 = 0.96$) could reduce the power to 72% of the original amount ($P/P_0 = 0.72$).[1] Increased thermal resistance of the thermoelectric material during life tends to maintain the beginning of life (BOL) temperature drop across the thermopile. This tends to compensate for the isotope decay effects on power reduction, and the total power loss at 5 yr is estimated to be 75% of the BOL power ($P/P_0 = 0.75$), compared to TRW Systems' estimate of 0.80 and GGA's estimate of 0.86. Using the BOL specific power of 2.93 W/kg, the 5-yr value reduces to 2.20 W/kg. This is shown in Fig. 1 along with estimates for the other systems. Although a 5-yr useful life is usually assumed for PbTe systems, the curves for Isotec, SNAP 19-TAGS, and SNAP 27 Integral are extended to 12 yr (dashed line) for the purpose of comparison with the SiGe performance. The basis for long-life predictions for the remaining systems is shown in the following subsections.

The use of an unsealed PbTe system even at low temperatures for mission times greater than 5 yr is questionable. In fact, the basis for 5-yr performance at anticipated levels is not well documented. Test data from the performance module, assembled with improved process control, will give greater confidence in long-life performance when sufficient test time has been accumulated.

4. SNAP 19-TAGS Technology

Isotopes, a Teledyne subsidiary, is developing the SNAP 19-TAGS technology for the *Pioneer F* and *G* missions. There are many SNAP 19 TAGS-85/2N converters that have been assembled and placed on test by Isotopes (SN 26 to SN 33). Only SN 26 has sufficient test time (1 yr) to be very useful in making a long-life performance predictions. Most of the test time on this converter is at a greater heat load ($Q = 675$ W) and as a result, a greater hot-junction temperature ($T_{HJ} = 841°K$) than the *Pioneer* reference design ($Q = 640$ W and $T_{HJ} = 805°K$). SN 29 provides some information on the power loss when changing the converter cover gas from argon to helium. This effect is important, since the helium

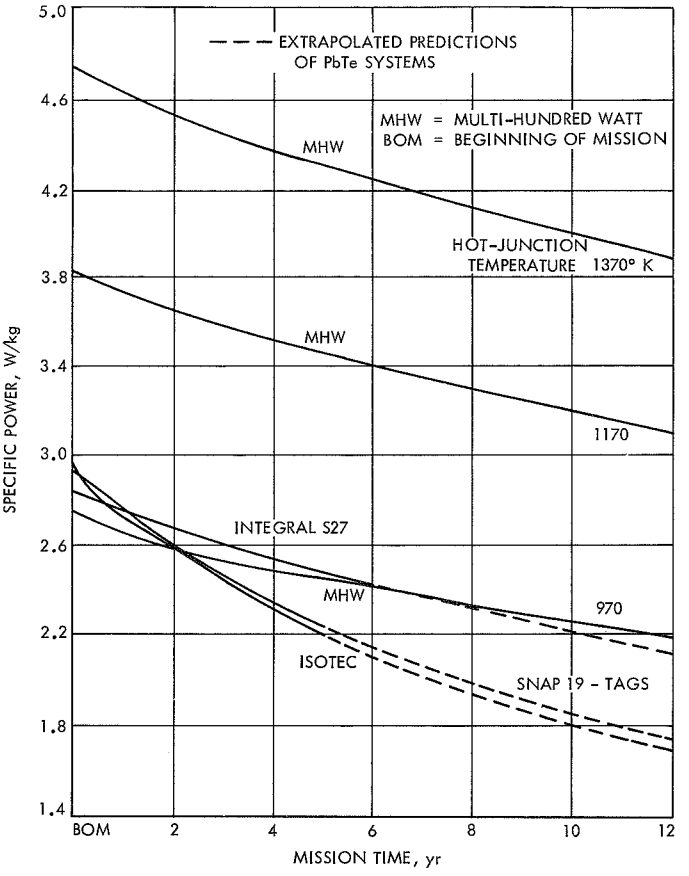

Fig. 1. RTG specific power 12-yr performance prediction

released by this RTG is vented into the thermopile region. Due to helium's high thermal conductivity, compared to the original cover gas, argon, there is a reduction in the temperature drop across the thermopile, which causes a power reduction. Some additional data is available from SN 31 being tested at JPL at T_{HJ} equal to 819°K.

Two methods are used to estimate the long-life performance. The first is based on SN 26 test data, the Isotopes analytical model at lower temperatures ($T_{HJ} < 794°K$), the power loss caused by helium release, and the power reduction due to isotope decay. This approach indicates 71% of the original power remaining 5 yr after launch (5.75 yr after fueling) based on 100% helium release. When considering end-of-mission (EOM) power, a more conservative design approach would be based on a 100% helium release rate. This accounts for about half of the difference between the Isotopes 5-yr estimate ($P/P_0 = 0.805$) and the previous estimate of $P/P_0 = 0.71$. The remaining half is due to differences in consideration of material effects.

[1] Q/Q_0 = (thermal power input at time t)/(initial thermal power input).
P/P_0 = (electrical power output at time t)/(initial electrical power output).

The second method used to estimate long-life performance is based on the percent material degradation versus temperature relationship from S/N 26, 29 and 31, and the power reduction due to helium release and isotope decay. The temperature versus time and percent degradation versus temperature relationships are integrated to yield a 7.5% power loss due to material degradation over 5 yr. The 100% helium release rate and isotope decay added to the material effects result in a reduction in power to 72% of the original value ($P/P_0 = 0.72$). This compares very well to the first method estimate of 0.71. Based upon these results and the specific power at fueling of 3.11 W/kg, the EOM value is 2.24 W/kg. This curve is also shown in Fig. 1. The beginning of mission (BOM) is 0.75 yr after fueling and some power loss has already occurred to reduce the specific power to 2.93 W/kg at BOM.

5. SNAP 27 Technology

There is an extensive amount of test data on the Minnesota Mining and Mfg. Co. (3M) couples used in the SNAP 27 program. There have been twenty-one 10-couple module tests that lasted as long as 3 yr. In addition, there have been fifteen 104-couple modules with test durations of nearly 3 yr. These tests investigated such design parameters as hot-junction temperature, cover gas pressure, and leg spring pressure. Also, complete engineering generators were placed on test, Models 5, 8B, and 10, with a Model 10 test time of 10,000 hr. Model 15 is on test at JPL at a reduced temperature ($T_{HJ} = 811°K$), which is an operating condition of interest for a long-term mission.

A model of generator performance has been made by the 3M Company based upon the 10-couple module tests. The best agreement between the data and the model exists when γ equals -0.4,

where

$$\frac{k}{k_0} = \left(\frac{R_0}{R}\right)^{\gamma}$$

k = thermal conductivity

R = electrical resistivity

zero subscript = beginning of life value

In addition, over half a year of performance is available from the flight unit used on *Apollo 12*. The power decay rate of this unit is less than 2% per year at an average temperature of 833°K; this coincides exactly with the 3M model. Based on these data and the model, the remaining power would be 89% of the original after 5 yr with the $T_{HJ} = 811°K$, and 85% after 8 yr.

Depending on the mission duration, the design BOM T_{HJ} would be varied to optimize performance at EOM. For short missions ($\sim$1 yr) the T_{HJ} would be set at 833°K, while missions of 5 yr or longer would have a T_{HJ} of 811°K. This type of relationship is used to show performance over a range of mission times.

The SNAP 27 generator used on *Apollo* did not have an integral heat source that could survive reentry conditions. A *Pioneer* study was used to include an integral heat source in a modified SNAP 27 converter. The heat source design used was similar to the AI technology, except that solid-solution fuel form is used; the specific power of the heat source is 177 W(t)/kg. This is higher than the heat sources being designed for *Pioneer* and *Transit* missions. Although it is normally possible to produce a lighter specific weight heat source as the fuel loading is increased, it is considered more appropriate if the heat source weight would better represent those on the committed missions. Therefore, the heat source specific power was changed from 177 to 132 W(t)/kg, and the heat source weight became 10.6 kg for $Q = 1400$ W(t). Based on this change, the BOM specific power for the RTG is 2.82 W/kg at T_{HJ} equal to 833°K. Based on the long-life effects established earlier, this reduces to 2.46 W/kg at 5 yr for T_{HJ} equal to 811°K. This relationship is also shown in Fig. 1.

The long test times on the SNAP 27 program give good confidence for a 5-yr capability, and the substitution of 2N thermoelectric material for the 3N in one leg of the couple would increase power by 15% without any weight increase. The five-year specific power would increase to 2.82 W/kg on this basis.

6. MHW Technology

The SiGe Air-Vac couples produced by the Radio Corporation of America (RCA) have a stable long-life capability which has been demonstrated by long-term testing. There have been a great number of couple-hours (5×10^6), and module tests (panels) have continued for as long as 49,400 hr with an average test time of 47,600 hr. The 68.8% silicon material has been used for much of this testing at hot-junction temperatures from 1120 to 1320°K. Therefore, there is a high degree of confidence in performance prediction for 5 yr. The material change phenomenon of dopant precipitation seems

to be well understood and gives credibility to a prediction for an even longer time such as 10 or 12 yr.

Based on a current evaluation of material aging effects and the Resalab, Inc., SiGe conductivity data, SiGe RTGs are optimized for various mission times. Using a 123 W(t)/kg capsule (which is typical of the AI technology as well as the MHW Helipak design), the RTG specific power is shown in Fig. 1. Curves are shown for T_{HJ} equal to 970, 1170, and 1370°K for the 80% material based on generators with multi-foil insulation. These results can also be used to represent the 63.5% material at lower temperatures, (~1270°K). The 970°K temperature level gives performance comparable to PbTe system performance over lifetimes associated with PbTe, but there is much greater confidence in long-time mission capability for the SiGe MHW.

The T_{HJ} level that may be used is entirely a function of the limiting temperature of the heat source. The capsules for the *Transit* and *Pioneer* programs are based on the AI technology which has a 5-yr mission design goal of 1366°K for the capsule surface temperature. The T_{HJ} of a SiGe RTG is expressed as a function of the capsule temperature in Fig. 2 for an AI-type capsule. A band is shown due to possible variations in heat source design. Based on this relationship, the specific power of the SiGe RTG is shown in Fig. 3 as a function of possible capsule temperature. At the 1366°K design goal for the AI capsule, the resulting T_{HJ} is approximately 1170°K with a three-year mission specific power of 3.36 W/kg, compared to about 2.46 W/kg for the PbTe systems. This design could be accomplished using 63.5% silicon material and the same heat source developed for the *Transit* and *Pioneer* missions.

The MHW program with a Helipak design heat source could extend performance so that an 1370°K T_{HJ} is possible (with 80% thermoelectric material); the 3-yr mission specific power is nearly 4.5 W/kg. The long-term mission of 12 yr would have performance of greater than 3.81 W/kg. Therefore, using the SiGe generator at temperatures acceptable for the 63.5% material (up to 1270°K) in a neutral environment such as Kaowool or Min-K insulation seems quite satisfactory for a long-term mission.

As the MHW program develops, the specific power estimate may vary somewhat from the values shown in Fig. 1. Also, as of this date, a complete analysis has not been performed on the use of the Atomics International-

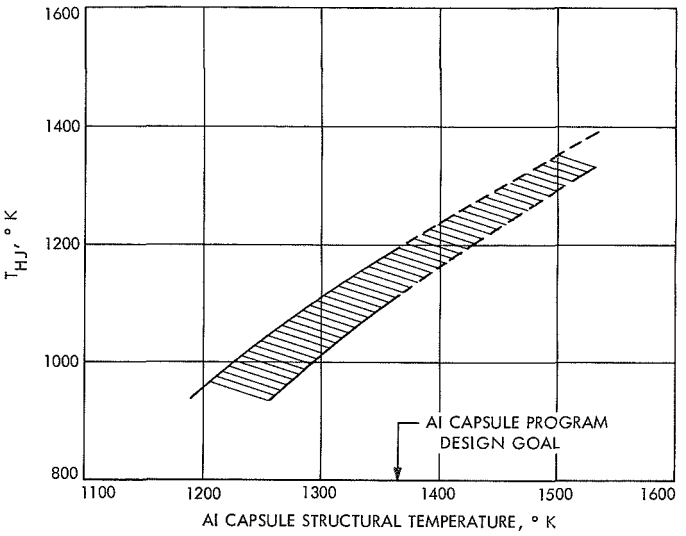

Fig. 2. T_{HJ} of MHW versus capsule Ta 111 temperature

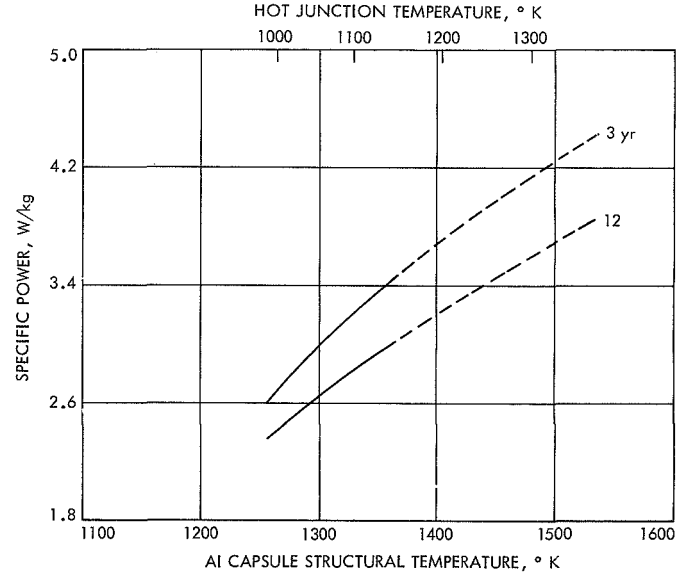

Fig. 3. MHW specific power versus possible capsule temperature

type heat source in the MHW converter. The temperature relationship shown in Figs. 2 and 3 may change somewhat as more design information becomes available. The use of alternate insulation, 80% material at 1370°K, is not well verified at this time. Only as material testing occurs and compatibility with other environments is verified can a long-term mission seriously be based on the 80% material used at 1370°K with foil insulation.

7. Conclusions

The SiGe Air-Vac converter has the strongest position of all thermoelectric technologies, especially for long-term missions ($\gtrsim$ 3 yr) based on the following:

(1) Long-term test time to date with relative confidence in long-term mission performance predictions.

(2) Basic stability of the SiGe material and predictability of long-term aging effects.

(3) Ability to accept whatever heat source technology is available for a particular mission.

(4) High specific power, even with current state-of-the-art heat source design.

(5) Flexibility of final design adjustments in the converter.

(6) Possible use of a nonsealed converter or, if a sealed unit is used, a converter that does not require a seal after launch.